THE DISTANCE TO THE LMC CLUSTER NGC 1866 AND THE SURROUNDING FIELD

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ABSTRACT

We use the Main Sequence stars in the LMC cluster NGC 1866 and of Red Clump stars in the local field to obtain two independent estimates of the LMC distance. We apply an empirical Main Sequence-fitting technique based on a large sample of subdwarfs with accurate *Hipparcos* parallaxes in order to estimate the cluster distance modulus, and the multicolor Red Clump method to derive distance and reddening of the LMC field. We find that the Main Sequence-fitting and the Red Clump distance moduli are in significant disagreement; NGC 1866 distance is equal to $(\mathrm{m-M})_{0,\mathrm{NGC\ 1866}} = 18.33\pm0.08$ (consistent with a previous estimate using the same data and theoretical Main Sequence isochrones), while the field stars provide $(\mathrm{m-M})_{0,\mathrm{field}} = 18.53\pm0.07$. This difference reflects the more general dichotomy in the LMC distance estimates found in the literature. Various possible causes for this disagreement are explored, with particular attention paid to the still uncertain metallicity of the cluster and the star formation history of the field stars.

Subject headings: galaxies: clusters: individual(NGC 1866) – galaxies: distances and redshifts – galaxies: individual (Large Magellanic Cloud) – galaxies: stellar content

1. INTRODUCTION

The distance to the Large Magellanic Cloud (LMC) is the cornerstone of the extragalactic distance scale, owing to the fact that the zero point of both the Cepheid and Type Ia supernova distances is tied to the LMC distance. Unfortunately, existing determinations of this fundamental quantity show a large range of values (Benedict et al. 2002), which can be schematically clustered around $(\mathrm{m-M})_{0,\mathrm{LMC}}$ ∼18.25–18.35 (short distance scale) and $(\mathrm{m-M})_{0,\mathrm{LMC}}$ ∼18.50–18.60 (long distance scale). We recall that the *HST* extragalactic distance scale project has determined a value for the Hubble constant $H_0 = 72 \pm 3(\mathrm{random}) \pm 7(\mathrm{systematic})$ by assuming $(\mathrm{m-M})_{0,\mathrm{LMC}} = 18.50\pm0.10$ (Freedman et al. 2001).

This dichotomy is best illustrated by the recent results by Walker et al. (2001, hereinafter W01), Alves et al. (2002) and Salaris & Girardi (2002, hereinafter SG02). W01 have determined the distance to the LMC cluster NGC 1866 by using the well established Main Sequence-fitting (MS-fitting) technique; NGC 1866 is a well populated young cluster located about 4^0 north of the center of the LMC, in a region with low extinction. Assuming that the cluster lies in the LMC plane the geometrical correction to the LMC centre is small, amounting to ~ -0.02 mag in distance modulus. W01 MS-fitting technique was based on theoretical isochrones which were shown to match properly the MS of the Hyades corrected for the Hipparcos distance modulus; a NGC 1866 distance modulus $(\mathrm{m-M})_0 \sim 18.30-18.35$ was obtained, a typical example of the short distance scale.

On the other hand, Alves et al. (2002) and SG02 have obtained $(\mathrm{m-M})_{0,\mathrm{LMC}} \sim 18.50$ by using multicolor photometry of LMC Red Clump (RC) field stars (observed in two different fields) as standard candles, a distance in agreement with the long distance scale and the *HST* zero point. They have both used the local RC Hipparcos absolute brightness, corrected by the appropriate population corrections for the LMC computed by Girardi & Salaris (2001, hereinafter GS01) and SG02. The use of multicolor photometry allows one to derive simultaneously both distance modulus and reddening of the observed population, as shown by Alves et al. (2002). Moreover, Sarajedini et al. (2002) derive similar values by using IR observations of the red clump in two LMC star clusters.

The present investigation aims at studying in more detail this discrepancy between MS-fitting and RC distances to the LMC. We take advantage of the fact that the NGC 1866 VI (Johnson-Cousins) data published by W01 show not only the well populated MS of NGC 1866, but also a clearly defined RC of the surrounding LMC field; this occurrence allows us to simultaneously apply MS-fitting and RC method to the same photometric data for the same LMC region. The advantage with respect to comparing MS-fitting and RC distances from different investigations is that in this way we minimize possible systematic discrepancies arising from different photometric zero points, differential errors in the reddening estimates to the observed fields, and depth effects due to the morphology of the LMC. In particular, we have redetermined the MS-fitting distance to NGC 1866 using a completely empirical procedure (as opposed to the MS-fitting based on theoretical MS models performed by W01) which makes use of a large sample of local subdwarfs with accurate parallaxes presented in Percival et al. (2003, hereinafter P03).

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At the same time, we have applied the RC method to the field RC stars, by using GS01 and SG02 results. The comparison of these distances will provide more solid evidence about the consistency – or lack of it – of the results from the two methods. Sections 2 and 3 present the distance estimates obtained from, respectively, MS-fitting and RC techniques. A comparison and discussion of the results follow in Section 4.

2. MS-FITTING DISTANCE

We have used in our analysis the WFPC2 *HST* photometry by W01 (see also Brocato et al. 2003 for more details). Their V-$(V-I)$ (Johnson-Cousins) Color Magnitude Diagram (CMD) shows a well delineated cluster MS and the LMC field Red Giant Branch and RC stars. In Figure 1 we show the main line of the cluster MS as determined by W01, together with the surrounding field population.

W01 have adopted a cluster metallicity [Fe/H]=-0.50 ± 0.1 as derived from high dispersion spectroscopy of three cluster giants performed by Hill et al. (2000); by fitting a theoretical isochrone with [Fe/H]=-0.5 to the cluster fiducial line (see Fig. 1) both the reddening E$(V-I)$=0.08$\pm$0.01 and the distance modulus $(\mathrm{m}-\mathrm{M})_{\mathrm{V,NGC\ 1866}}$=18.50$\pm$0.05 are obtained. The interested reader can find more details concerning the adopted procedure in W01.

This corresponds to $(\mathrm{m}-\mathrm{M})_{0,\mathrm{NGC\ 1866}} = 18.30 \pm 0.05$ and E$(B-V)$=0.064$\pm$0.011 (we adopt A_I/E(B-V)=1.8, A_V/E(B-V)=3.1 from Cardelli, Clayton & Mathis 1989); the E$(B-V)$ value, in particular, is in good agreement with previous empirical determinations (van den Bergh & Hagen 1968, Walker 1974).

W01 isochrones were also shown to fit properly the Hyades MS with the Hipparcos distance, when the spectroscopic metallicity [Fe/H]=+0.13 is used for the isochrones. The reliability of this NGC 1866 distance rests therefore entirely on the adequacy of the scaling of W01 isochrones with [Fe/H], in the metallicity range spanned by the Hyades and NGC 1866. Here we have rederived the MS-fitting distance to NGC 1866 by following a completely empirical procedure. We have considered the field dwarf sample with accurate BVI (Johnson-Cousins) photoelectric photometry and Hipparcos parallaxes presented by P03; these 54 objects span a [Fe/H] range between ~-0.5 and $\sim$+0.3, and have absolute magnitudes in the range between $M_V\sim$5.5 and $M_V\sim$7.5, thus they are unevolved zero-age MS stars. Their CMD location is therefore totally insensitive to an age difference between NGC 1866 (age of the order of 100 Myr) and the local field stars, whose average age is higher than the cluster one, being probably of the order of a few Gyr (see, e.g., the discussion by Stello & Nissen 2001).

When determining the MS-fitting distance to a cluster, a template MS is constructed from the field dwarf sample by applying color shifts to the individual stars, to account for the differences in metallicity between the field stars and the cluster. The procedure used to calculate the magnitude of these metallicity dependent color shifts employs a purely empirical method fully described in P03, to which we refer the interested reader for full details. The basic method relies on first establishing that the shape of the MS is insensitive to [Fe/H] in the narrow range of metallicities and magnitudes we are dealing with. Next, we determine the color that each field dwarf would have at a fixed magnitude of $M_V=6$, which we call $(V-I)_{M_V=6}$, using the slope of the Hyades ([Fe/H]=+0.13) MS as a reference slope. Finally, we calculate the derivative $\delta(V-I)_{M_V=6}/\delta[Fe/H]$ which, from the full field dwarf sample, yields a value of $\delta(V-I)_{M_V=6} = 0.103\delta[Fe/H]$. Because of the unvarying shape of the MS, this derivative is appropriate for the whole magnitude range spanned by the field dwarf sample, and hence color shifts are applied to each star in the sample, at their observed magnitudes, to construct a template MS at the metallicity of the cluster.

By using [Fe/H]=-0.50 ± 0.1 and E$(V-I)$=0.08$\pm$0.01 (the result of the fit of the field dwarfs to the cluster MS is displayed in Fig. 1) we obtain an empirical MS-fitting distance modulus $(\mathrm{m}-\mathrm{M})_{0,\mathrm{NGC\ 1866}} = 18.33 \pm 0.08$, in agreement with the results by W01 based on theoretical isochrones.

3. RC STARS DISTANCE

As proposed by Stanek & Garnavich (1998), a non-linear least-square fit of the function

$$N(m_\lambda) = a + bm_\lambda + cm_\lambda^2 + d\exp\left[-\frac{(m_\lambda^{\mathrm{RC}} - m_\lambda)^2}{2\sigma_{m_\lambda}^2}\right] \quad (1)$$

to the histogram of stars in the clump region per magnitude (m_λ) bin has provided, among others, the apparent magnitude of the RC m_λ^{RC}, and its associated standard error, in both the V and I photometric bands. We adopted $M_I^{\mathrm{RC}} = -0.26 \pm 0.03$ and $M_V^{\mathrm{RC}} = 0.73 \pm 0.03$ for the absolute brightness of the local Hipparcos RC (Alves et al. 2002), together with the population corrections by GS01 and SG02 which take into account the expected difference between the absolute magnitude of the RC in the solar neighbourhood and the LMC field; these corrections add 0.20 mag (I-band) and 0.26 mag (V-band) to the apparent distance moduli obtained from the local RC brightness. These corrections have been calculated by GS01 and SG02 from a complete population synthesis algorithm, which produces a synthetic CMD (hence a luminosity function for the RC stars) for the LMC and the solar neighborood populations, using the theoretical stellar models by Girardi et al. (2000). GS01 and SG02 have employed for the LMC the Star Formation Rate (SFR) determined by Holtzman et al. (1999; their fig. 2), and the Age Metallicity Relationship (AMR) by Pagel & Tautvaisiene (1998); in the case of the solar neighborood the SFR and AMR of Rocha-Pinto et al. (2000a,b) have been used. More details about these issues and the comparison of the synthetic local RC with the *Hipparcos* results are given in sections 2.2, 3 and 5.4 of GS01.

Following Alves et al. (2002), after the apparent distance moduli have been determined, one then enforces the constraint that the distances determined simultaneously in V and I must all provide the same unreddened distance; by assuming the same reddening law as in Section 2, we obtain simultaneously $(\mathrm{m}-\mathrm{M})_{0,\mathrm{field}}$ = 18.53$\pm$0.07, and E$(B-V)$=0.05$\pm$0.02. Notice the very good agreement between the reddening derived with this procedure and the independent estimates for NGC 1866 reported in the previous section.

4. DISCUSSION

Some important results emerge from the previous two sections. The first one is that empirical and theoretical MS-fitting techniques provide exactly the same distance to NGC 1866, thus confirming the accuracy of the isochrones employed by W01 and in general the reliability of this method. The second one is that the RC method applied to the field around the cluster estimates a reddening which is in good agreement with the value for the cluster, and with the mean foreground $E(B-V)$ to the LMC, which is 0.06±0.02 mag, according to Oestreicher, Gochermann & Schmidt-Kaler (1995). The third result is that a disturbing discrepancy between the MS-fitting distance to NGC 1866 and the RC distance to the surrounding LMC field does exist. The difference Δ between the LMC distances derived from the two methods amounts to $\Delta = 0.20\pm0.10$; it is therefore significant at 2σ confidence level. Recalling that these two independent methods are often used individually to obtain LMC distances with small internal errors, the consistency between the two results appears too marginal to be satisfactory.

Let's discuss now separately possible systematic errors that can bring in agreement the distances obtained with the two methods. Concerning the RC distance, we have mentioned the derived reddening of the field stars, in agreement with completely independent estimates for the cluster, which can be claimed as an argument for the reliability of the RC distance. In principle, however, the reddening derived from the RC does not depend on the absolute values of the population corrections in V and I, but only on their difference. Population corrections smaller by $\sim$0.1 mag in both V and I, but still differing by of 0.06 mag, would provide the same reddening and a RC distance modulus in agreement with the MS-fitting one within 1σ.

The population corrections applied to the LMC RC depend on the theoretical prediction of the variation of the RC mean brightness for simple (single-age, single-chemical composition) stellar populations of varying [Fe/H] and age, and on the estimate of the SFR and AMR for the observed LMC field stars. GS01 and SG02 have clearly demonstrated with various empirical tests how the V and I brightness of the RC in Galactic open clusters spanning a range of age and metallicity is well reproduced by their theoretical corrections. GS01 have also discussed in depth the issue of the LMC SFR and AMR, by using determinations for different LMC fields by Holtzman et al. (1999), one of which is very close to our observed target. It turns out that for all the observed fields the individual population corrections are very similar, within about ±0.02 mag in both the V and I bands, and the difference between the I- and V-band correction is constant. There is therefore no indication that our RC distance determination is affected by sizable systematic errors, unless the SFR and AMR adopted to model the RC are in serious error. It is perhaps interesting to note that the distance we obtain from the RC is in good agreement with what would be obtained by using only the K-band data by Alves et al. (2002) for their observed LMC field; the interest of this comparison rests on the fact that reddening effects are negligible in the K-band, and moreover the population corrections are also negligible, at least for the SFR and AMR employed by GS01 and SG02.

We have also, as an experiment, made use of the SFR and AMR estimated by Dolphin (2000a) for a LMC field not far from NGC 1866, which, after computing the appropriate population corrections (GS01), provide $(m-M)_{0,\mathrm{field}} = 18.29\pm0.07$, and $E(B-V)$=0.13±0.02. In this case the distance modulus is in good agreement with the NGC 1866 one, but the reddening is higher by a factor of $\sim$2, an occurrence difficult to justify and, moreover, the morphology of the RC as obtained from the theoretical simulations does not match the observed one, as discussed by GS01.

As far as the MS-fitting distance is concerned, with our empirical procedure we have explored the effect of varying separately the cluster [Fe/H] and reddening, which are both parameters to be fixed beforehand. By keeping the reddening value constant at $E(V-I)$=0.08 ($E(B-V)$=0.064), we obtain that one needs a cluster metallicity between [Fe/H]~ -0.2 and [Fe/H]$\sim +0.2$ for having the value of Δ between zero and the associated $\pm1\sigma$ error. If [Fe/H] is kept fixed at -0.5 ± 0.1, and the reddening allowed to vary, one needs a reddening $E(V-I)$ of at least 0.10 mag ($E(B-V)$=0.08) for the distances to agree within the 1σ error. If both [Fe/H] and reddening are allowed to vary independently, intermediate combinations of these two quantities can solve the discrepancy.

There is a further constraint to be applied to the cluster reddening. In fact, the results from our empirical procedure have demonstrated the reliability of the theoretical isochrones employed by W01, at least in the [Fe/H] range between the Hyades metallicity and [Fe/H]~ -0.5. Owing to the fact that a fit of the theoretical MS to the cluster CMD provides both distance modulus and reddening, we can use theory in order to further constrain the variation of [Fe/H] and reddening necessary to bring the two distance methods into agreement. We find that by changing the cluster [Fe/H] from -0.5 to solar, the derived $E(B-V)$ changes by only 0.008; the value of Δ decreases to within the 1σ error when [Fe/H] increases to at least [Fe/H]~ -0.2. A negligible variation of $E(B-V)$ with respect to the reference value of 0.064 mag is found when this metallicity is adopted in the fit. This minimum cluster metallicity is exactly the value obtained from the empirical MS-fitting in case of the reddening being kept fixed.

Is this value for the cluster [Fe/H] acceptable in light of the existing empirical constraints? The most direct metallicity determination for the cluster is the high resolution spectroscopy result adopted by W01 and by us, namely [Fe/H]=-0.5 ± 0.1, which is however based on only 3 giant stars, and therefore cannot be considered conclusive. A couple of other independent estimates based on the integrated cluster spectrum (Oliva & Origlia 1998) and on Strömgren photometry of supergiants (Hilker, Richtler & Gieren 1995) provide values in broad agreement with the high resolution result, albeit with much larger error bars by ±0.4 and ±0.18 dex, respectively. On the other hand, if one employs the same Hilker et al. (1995) Strömgren photometry of NGC 1866 supergiants, in conjunction with the [Fe/H]-Strömgren photometry calibration by Arellano Ferro & Mendoza (1993), an approximately solar [Fe/H] is obtained. In addition, Feast (1989) has used BVI photometry of Cepheids in the cluster and determined their metallicity following the procedure by Caldwell & Coulson (1985), obtaining a mean abundance [Fe/H]=-0.1 ± 0.2. In light of these existing uncertainties about NGC 1866 metallicity, new spectroscopic observations of a wide sample of cluster stars (for example by using FLAMES@VLT) are urgently needed.

We want also to mention the uncertainties due to the calibration of the photometric measurements. We consider a possible systematic zero-point error on the V and I WFPC2 magnitudes of ± 0.02 mag (Dolphin 2000b). Such a shift in the V magnitude would marginally affect the distance values and do not help in decreasing substantially the gap between the MS and RC distances. On the other hand, a corresponding zero-point error by 0.03 mag on the $(V-I)$ color is expected to produce sizable differences for the MS-fitting distances due to the slope of the MS itself. To quantitatively explore the effect of this source of uncertainty on our distance evaluations we derived again the distances with both the MS of NGC 1866 and the RC of the surrounding field; by considering zero-point errors of ± 0.02 mag on both V and I magnitudes, the systematic error on the distance moduli difference Δ previously defined amounts to ± 0.19 mag. Clearly this may overcome the discrepancy between the two methods only in the case that the assumed photometric zero-point is in error by -0.02 mag. The comparison with ground based photometry (Walker 1995) as performed by W01 does not provide any significant information, since the spread ($\sigma \sim 0.06$) is so large that it prevents for any realistic conclusion on the matter.

As a last point, let us recall that the previous discussion relies on the assumption that both the cluster and the RC field stars are located at the same distance from us. If this is not the case, the discussed dichotomy would indicate that the cluster is about 5 Kpc closer to us than the underlying field population of the LMC. To investigate this possibility one will need to determine MS-fitting distances to a larger sample of LMC clusters, so that depth effects due to the spatial distribution of the clusters cancel out when a mean value of their distances is computed.

In conclusion, we find that the dichotomy of the distance of the LMC largely debated in the literature arises also when the distance to one single cluster (NGC 1866) and the surrounding LMC field are compared. This may suggest that global uncertainties in the methods of determining distances are underestimated. NGC 1866 also contains more than 20 Cepheids and this make this cluster a critical benchmark to probe the distance of the LMC. Available works on Cepheids in NGC 1866 (Gieren et al. 2000 and references therein) do not solve definitely the question, given that the derived distances show a sizable uncertainty. Thus, specific high resolution spectroscopy and detailed light curves of the cluster's Cepheids are required.

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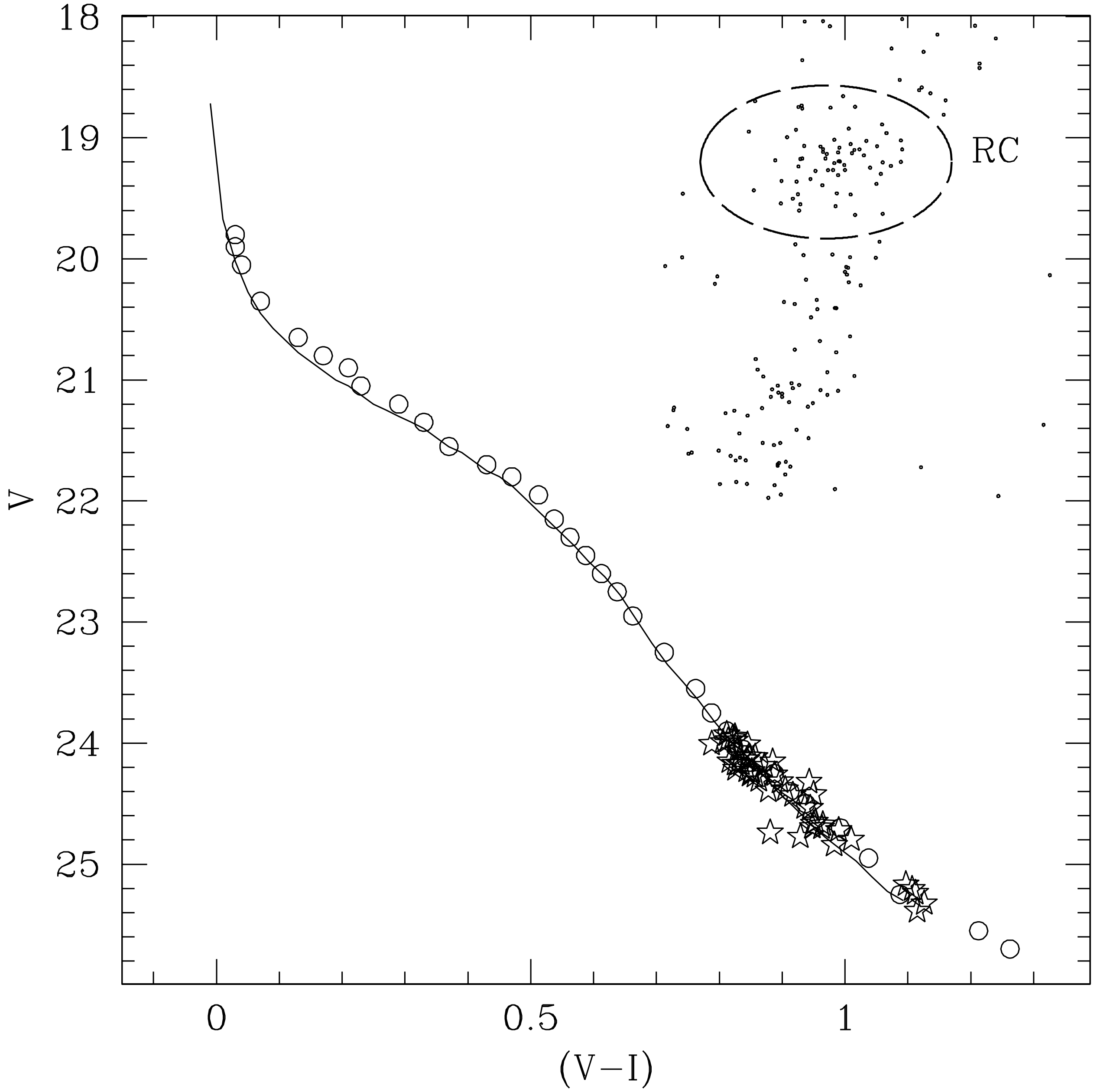

FIG. 1.— VI (Johnson-Cousins) CMD of NGC 1866 MS (only the main sequence line is plotted as open circles), together with the Red Giant Branch and RC stars of the surrounding LMC field. The solid line denotes the best fitting isochrone with [Fe/H]=−0.50; star symbols show the sample of local subdwarfs used as standard candles, fitted to the cluster MS (see text for details).